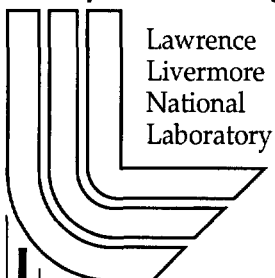


# **Longevity Tests of High-Sensitivity BD-PND Bubble Dosimeters**

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**U.S. Department of Energy**



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# Longevity Tests of High-Sensitivity BD-PND Bubble Dosimeters

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## SUMMARY

Medium- and very-high-sensitivity neutron bubble dosimeters (BD-PNDs) made by Bubble Technology Industries (BTI) were used to study the life span of such dosimeters in a standard setup with a  $^{252}\text{Cf}$  source. Although data on the longevity of bubble dosimeters with low and medium sensitivity exist, such data for dosimeters with high and very high sensitivity are not readily available. The manufacturer guarantees optimum dosimeter performance for 3 months after receipt. However, it is important to know the change in the dosimeters' characteristics with time, especially after the first 3 months. The long-term performance of four sets of very high sensitivity and one set of medium-sensitivity bubble dosimeters was examined for periods of up to 13 months. During that time, the detectors were exposed and reset more than 20 times. Although departures from initial detection sensitivity were observed in several cases, the detectors indicated a significantly longer life span than stated in the manufacturer's warranty. In addition, the change in the number of bubbles and in evaluated neutron dose as a function of the time from the end of exposure until the dosimeters were read was investigated.

## INTRODUCTION

Bubble dosimeters, or superheated drop detectors, were first described by Robert Apfel [1] in 1979. During the last decade, bubble detectors reached a level of development that makes them attractive for practical applications in neutron dosimetry. Bubble dosimeters are commercially available from BTI of Chalk River, Canada, and Apfel Enterprises of New Haven, CT, and are becoming an increasingly useful tool in neutron dosimetry and spectrometry [2–33]. Bubble dosimeters are unique in their high sensitivity to neutrons and insensitivity to gamma radiation. An advantage of bubble dosimeters over other passive individual neutron dosimeters is that they allow the immediate, direct reading of dose. Bubble dosimeters have been used for detecting 2.5 MeV neutrons from D-D fusion and 14 MeV neutrons from D-T fusion; for mapping neutron fields near nuclear reactors, spent fuel, and particle accelerators [21]; and as dosimeters for commercial nuclear power reactors [13] and nuclear installations [10]. Research [20] has established that the bubble detector is the only type of personal neutron dosimeter with adequate sensitivity (i.e., low detection threshold) to meet the implications of ICRP 60 (ICRP, 1991) recommendations for neutron dosimetry.

## DESCRIPTION OF BUBBLE DOSIMETERS

A bubble dosimeter consists of a transparent plastic tube containing a clear, elastic, jelly-like hydropolymer medium throughout which tiny droplets of a superheated liquid have been dispersed. The bubble dosimeters employed in this study were BD-PND bubble dosimeters from BTI [35]. These BD-PND dosimeters consist of a clear plastic vial containing 8 cm<sup>3</sup> of a sensitive suspension of about 10<sup>4</sup>–10<sup>5</sup> superheated tiny droplets approximately 20 μm in diameter dispersed throughout the clear elastic polymer. The polymer in the vial is kept under pressure to prevent the droplets from growing under normal conditions (i.e., before the detectors are prepared for exposure to neutrons). The pressure on the elastic polymer is controlled by a cap assembly on top of the vial. The BD-PND dosimeter from BTI has built-in temperature compensation, which keeps response sensitivity within ±20% between 20°C and 37°C (see Figure 1, provided by BTI). The number of the bubbles obtained from the BD-PND dosimeter is proportional to the neutron dose over a wide neutron range (see Figure 3, provided by BTI). The proportionality constant (i.e., sensitivity) is indicated on the label of every bubble dosimeter. Each dosimeter is shipped in an airtight aluminum storage tube and with the polymer medium containing the superheated droplets pressurized (i.e., with the cap screwed onto the top of the dosimeter).

### Principle of Operation and Use

By unscrewing the cap assembly of the BD-PND dosimeter, the pressure on the polymer is released, and the liquid droplets become superheated. When the BD-PND dosimeter is exposed to a neutron flux, neutrons strike the polymer, and the superheated droplets vaporize due to the high linear energy transfer (LET) recoils from neutron interactions. Small visible bubbles are thus produced instantly in the sensitive medium. The number of the bubbles produced is proportional to the neutron dose equivalent as shown in Figures 3 and 4 (provided by the manufacturer). The bubbles are fixed in the elastic medium and can be subsequently counted visually or by an automatic image reader. The dose is determined by multiplying the number of bubbles by the dosimeter's sensitivity (i.e., the proportionality constant between the number of the bubbles and delivered dose). A model BDR-III automatic reader made by BTI (Figure 6) was used to count the bubbles in most of the tests. The BDR-III reader consists of an optical unit, a frame-grabber card (which is installed in a personal computer), and software. A mirror in the optical unit provides two views of the bubble detector for increased accuracy. A CCD camera records two images from the detector, and the software counts the bubbles in these images. To reuse the dosimeter, the bubbles must first be recompressed into droplets by screwing the cap assembly back on the dosimeter. The detector is activated again by unscrewing the cap assembly on the top of the dosimeter. The bubble dosimeters can be reused several hundred times, thus increasing their cost effectiveness.

### Calibration and Sensitivity of the Dosimeters

The BD-PND bubble dosimeters are calibrated by the manufacturer with an Am-Be source having a fluence-weighted average energy equal to 4.15 MeV and a source strength of  $1.13 \times 10^7$  n/s. Dosimeters are calibrated by BTI without the use of a phantom and with a combination of time and distance from the source that produces approximately

100–150 bubbles. The source and the dosimeters are held upright and parallel to each other in a styrofoam jig. The conversion factor used for the Am-Be source is  $3.70 \times 10^{-5}$  mrem/(n.cm<sup>-2</sup>), as calculated from dose equivalent defined in NCRP Report No. 38.

After the BD-PND bubble dosimeters are made in an automatic production line (but prior to incorporation of temperature compensation components), the dosimeters are exposed to the neutron source to determine their detection sensitivities. BTI's bubble dosimeters can be prepared in a range of sensitivities, from 0.33 to 100 bubbles/mrem, and are grouped by sensitivity into the four categories shown below (bubble dosimeters with sensitivities greater than 33 bubbles/mrem are available only on special order from BTI):

Sensitivity	Range (bubbles/mrem)
Low	0.33–1.0
Medium	1.2–3.9
High	4.7–10
Very high	12–33

After sensitivity determination, the necessary temperature compensation components are incorporated into the “raw” BD-PND dosimeters, which are then calibrated five times using the Am-Be source: one calibration each at 20°C, 24°C, 28°C, 35°C, and 37°C. A bubble dosimeter's indicated sensitivity is the average response over the temperature range 20–37°C. In Figure 2 (provided by BTI), the temperature response of the BD-PND dosimeters is shown for comparison with that of a non-compensated bubble dosimeter (BD100 from BTI). Figures 3 and 4 (provided by BTI) indicate that the BD-PND dosimeter's linearity with dose is excellent with and without repressurization of the dosimeters between exposures. The BD-PND bubble dosimeters provide a good estimate of the dose equivalent for neutrons with energies greater than 100 keV, as shown on Figure 5 (courtesy of BTI).

### **Life Span (Longevity) of BD-PND Bubble Dosimeters**

The end of a bubble dosimeter's useful life occurs when the bubbles can no longer be compressed back into droplets, when the elastic polymer starts leaking, or when, for any other reason, the bubble dosimeter does not properly record the neutron dose.

BTI guarantees optimum dosimeter performance for 3 months after receipt. The manufacturer recommends that the dosimeters be repressurized after use and stored inside the accompanying airtight aluminum storage tubes. According to the manufacturer, the dosimeters should have a shelf life of at least 6 months (assuming no exposure to neutrons and no depressurization). Several studies indicate that the useful life span of the BD-PND bubble dosimeters is longer than the manufacturer's 3-month warranty [2,10,11]. In the Vanhavere study [2], low- and medium-sensitivity BD-PNDs were irradiated 60 to 70 times over a 2-year period before reaching the end of their useful life. The total number of accumulated bubbles in each dosimeter used in the Vanhavere study

was approximately 6,800. Tests of BD-PND dosimeters used in uranium plants in Russia showed that at low doses (less than 100 mrem), BD-PNDs with a sensitivity about 3 bubbles/mrem meet BTI's advertised accuracy ( $\pm 20\%$ ) and the performance requirements of ANSI N13.11-1993, with the exception of use after being dropped from a height of 2 meters and use in extreme temperatures [10]. Results of these tests indicate that after 6 months the tested BD-PND dosimeters were not only functioning, but responded with the same accuracy and precision.

## TEST GOALS

Although other studies have examined the life span of BTI bubble dosimeters with low (0.3 bubbles/mrem) and medium (3 bubbles/mrem) sensitivity [2,10,11], data for high- and very-high-sensitivity bubble dosimeters are not readily available. One of the studies shows that change in sensitivity with time varies according to bubble dosimeter sensitivity. Therefore, an investigation of the change in the sensitivity of bubble dosimeters of high and very high sensitivity with time is important. This study concentrates on how long the BD-PND bubble dosimeters with very high sensitivity ( $>12$  bubbles/mrem) can be used after initial calibration (i.e., calibration by the manufacturer) and how much their sensitivity changes with time. Other interesting questions are how long bubble dosimeters can hold their dose information before reading, i.e., whether BD-PND sensitivity changes with the amount of time between the end of exposure and reading.

## EXPERIMENTAL SETUP

The BD-PND dosimeters in this study were irradiated with a  $^{252}\text{Cf}$  source at Lawrence Livermore National Laboratory's (LLNL's) low-scatter calibration facility [34]. The  $3 \times 10^9$  n/s californium source can be positioned pneumatically in the center of a 20x20x20 ft heavily shielded cell for irradiations. The floor of the cell consists of a metal grid with 5 ft of empty space below, thus reducing scatter from the floor. Irradiation time and source transport were controlled by a computer (Figure 7). The neutron doses delivered to the BD-PND dosimeters were determined using software that takes into account the neutron source energy distribution, distance from the source, source decay, and any scatter from the walls and floor of the irradiation cell [34].

All laboratory tests were done at a temperature of  $21^\circ\text{C} \pm 0.5^\circ\text{C}$ . The irradiations were conducted over a period of 13 months. The following five sets of dosimeters of various sensitivities were tested (see Table 1):

Set identification	Number of dosimeters in the set	Average sensitivity (bubbles/mrem)
B#1	12	2.5
BH#1	2	19.5

BH#2	2	16.0
BH#3	5	25.6
BH#4	5	18.8

Each set was randomly selected from pools of 32 to 80 dosimeters (see Table 1). Between irradiations, the dosimeters were kept in their airtight aluminum storage tubes at room temperature. The dosimeters were irradiated at distances of 100, 200, and 300 cm from the Cf source. The irradiation times were between 10 and 15 minutes. In most cases, the number of accumulated bubbles in the dosimeter volume ranged between 50 and 150. A typical irradiation setup is shown in Figure 8.

## TEST RESULTS

The test results are presented in Figures 9–24. Results for bubble dosimeters with medium sensitivity are presented in Figures 9 and 10. Results for bubble dosimeters with very high sensitivity are presented in Figures 11–24. The change in bubble dosimeter sensitivity as a function of time after initial calibration is shown in Figures 9–16. The results depicted in Figures 17–24 show the extent to which exposure information held by the bubble dosimeters changes if the dosimeters are not read immediately after exposure.

### Change in Sensitivity with Time after Initial Calibration

After exposure, the dosimeters were read on the same day, usually within 1–3 hours of the end of irradiation. Some of the readings were performed manually (i.e., by visually counting the bubbles); however, an automatic reader was used for the majority of the readings. No observable difference between manual and automatic readings was found. In the visual reading mode, each bubble dosimeter was read at least three times, and the average number of the bubbles was used to determine the dose for each particular dosimeter. When the BDR-III automatic reader was used, each dosimeter's bubble count was taken five times. Between counts, the dosimeter was rotated along its axis by approximately 70° to position all segments of its surface towards the camera. This was done to avoid any potential miscount due to the shielding of inner bubbles by bubbles located closer to the camera. The average number of these five bubble counts was used to determine the dose for each dosimeter. The dose determined by reading the BD-PNDs was compared with the delivered dose. The relative difference between delivered and determined doses, calculated thus

$$\frac{D_{\text{measured}} - D_{\text{delivered}}}{D_{\text{delivered}}}$$

was used as a measure of the change in sensitivity of the tested bubble dosimeters. The change in sensitivity for five groups of BD-PNDs was monitored for various time periods up to 13 months after initial calibration. The exposure and testing of the bubble

dosimeters in general began upon their receipt at LLNL—usually between 10 and 20 days after initial calibration. However, tests of bubble dosimeters of medium sensitivity began about 6 months after initial calibration. No leakage was observed in any of the tested bubble dosimeters, even as long as 1 year after receipt. The experimental results are presented as an average of the sensitivity change for all dosimeters in a particular group. The error bars in Figures 9–16 represent only the standard deviation of this average. The standard deviation of the average bubble count for a single dosimeter reading was about 5% and was not included in the error bars.

### ***Bubble Dosimeters with Medium Sensitivity***

The average change in sensitivity (in percent) for 12 bubble dosimeters (B#1) randomly chosen from a group of 80 dosimeters with medium sensitivity is shown in Figure 9. The monitoring began 6 months after initial calibration and continued for another 6 months. Figure 10 shows how many dosimeters exhibited a change in sensitivity greater than 20% in each of the tests. The data indicate that the change in sensitivity of bubble dosimeters with medium sensitivity stays within 20% for about 10 months after initial calibration.

### ***Bubble Dosimeters with Very High Sensitivity***

The average change in sensitivity for two bubble dosimeters (BH#1) randomly chosen from a group of 32 dosimeters with very high sensitivity is presented in Figure 11. The testing was carried out 15 to 350 days after initial calibration. Although individual results varied considerably on some days, the average change in sensitivity for these dosimeters stayed within 20%.

The average change in sensitivity for another two dosimeters (BH#2) randomly chosen from a different group of 32 dosimeters with very high sensitivity is shown in Figure 12. The monitoring was conducted 20 to 260 days after initial calibration. The average change in sensitivity for these dosimeters did not exceed 22%.

Figure 13 presents the average change in sensitivity for five dosimeters (BH#3) randomly chosen from a group of 35 dosimeters with very high sensitivity. Seventeen tests were conducted between 10 and 165 days after initial calibration. All but three of the tests showed an average change in sensitivity of less than 10%, and all average test results were within 20% of initial calibration. Although in each test the average change in sensitivity for the five dosimeters did not exceed 20%, changes in sensitivity for some individual dosimeters exceeded 20%. The individual change in sensitivity for these five dosimeters is presented in Figure 14, in which each dosimeter's results are identified with a unique number. Figure 15 presents how many individual dosimeters showed a change in sensitivity greater than 20% in each of the tests.

The test results for another five dosimeters (BH#4) randomly chosen from a group of 35 dosimeters with very high sensitivity are presented in Figure 16. The average change in sensitivity for these dosimeters did not exceed 20% within 50 days of initial calibration.

## **Change in Sensitivity as a Function of Time Between End of Exposure and Reading**

### ***Bubble Dosimeters with Very High Sensitivity***

For these tests, five bubble dosimeters from group BH#3 were initially read with the BDR-III automatic reader within 1 hour of the end of exposure to a neutron field. Without being recompressed, the same dosimeters were read again 2 to 150 hours after the initial reading. The relative difference between the initial reading ( $D_{in}$ ) and the reading after X hours ( $D_x$ ), defined thus

$$\frac{D_x - D_{in}}{D_{in}}$$

was used as measure of the change in bubble dosimeter sensitivity as a function of the time elapsed from the end of exposure until reading. In other words, this change in sensitivity provides a measure of the error in determined dose when a dosimeter is read a given amount of time after the end of exposure. As with all counts of bubbles with the BDR-III reader, the dosimeters were read five times, each time rotating the dosimeter approximately 70° and taking the average of the five counts. Group BH#3 of five bubble dosimeters was irradiated 10 times and was counted up to 40 times between 2 and 150 hours after the initial count.

The results from the two most extensive counts (6/13/00 and 6/30/00) are presented in Figures 17–24. In Figures 17–21, the results from the test on 6/13/00 are presented for each of the five dosimeters. The error bars indicate the standard deviation of the average of the five bubble counts for each dose measurement. Figure 22 provides the average change in sensitivity of the five dosimeters from the test on 6/13/00, and Figure 23 provides the average change in sensitivity for the same dosimeters from the test on 6/30/00. The average change in sensitivity of dosimeter group BH#3 in all 10 tests is shown in Figure 24. The error bars in Figures 22–24 represent the standard deviation of the average sensitivity change for all dosimeters in the group and do include the standard deviation of the average for the five bubble counts.

## **DISCUSSION OF TEST RESULTS**

As stated by the BD-PND manufacturer and shown in several studies, the type of neutron source used in calibration has only a small effect on the sensitivity value. For example, the sensitivities obtained from calibration with  $^{252}\text{Cf}$  and  $^{241}\text{Am-Be}$  sources differed between 2% and 9% [7,9,14].

As evidenced from Figure 9, the average sensitivity for 12 BD-PND dosimeters with medium sensitivity increased with time after initial calibration. This trend is consistent with the observed trend for the BD-PND dosimeters with low sensitivity [2]. The tested dosimeters with medium sensitivity exhibited sensitivity within  $\pm 10\%$  of initial calibration after 6 months of storage and within  $\pm 20\%$  of initial calibration after 6 months of storage and 4 months of testing (a total of 10 months of initial calibration). Even more

than 1 year after initial calibration, the sensitivity of the tested dosimeters did not differ more than 30% from that claimed by the manufacturer. Although the average sensitivity for the bubble dosimeters of low sensitivity shows a trend towards increasing with time, there is considerable scatter in the sensitivity changes of individual dosimeters. Figure 10 illustrates that after 10 months, half of the tested BD-PND dosimeters with medium sensitivity showed a sensitivity change of 20% or greater.

The first group, comprising two bubble dosimeters with very high sensitivity, was tested for 11.5 months and showed a trend towards increasing their average sensitivity (Figure 11). This trend is consistent with the trend for low- and medium-sensitivity bubble dosimeters, although the slope of the curve is not quite the same in all cases. The average change in sensitivity of the two dosimeters with very high sensitivity was within  $\pm 25\%$  of initial calibration 1 year after the calibration date. However, there is considerable scatter between the two dosimeters' sensitivity changes.

A second group of two bubble dosimeters with very high sensitivity exhibited a change in sensitivity of less than  $\pm 20\%$  almost 9 months after initial calibration. Average sensitivity does not show any definite trend with time after initial calibration (Figure 12). As in the previous test, there is scatter in the sensitivity change between the two dosimeters.

The average change in sensitivity for a group of five bubble dosimeters of very high sensitivity differed less than  $\pm 20\%$  from the sensitivity determined by the manufacturer during 5 months of testing (Figures 13 and 15). These dosimeters exhibited a trend towards decreasing in average sensitivity with time after initial calibration. However, the scatter between individual results (Figure 14) in any one test is large; in the worst case, it exceeded 190%.

The last group, comprising five dosimeters with very high sensitivity, was tested three times within 50 days of initial calibration. The results may be interpreted as a trend towards an increasing average sensitivity for the five tested dosimeters (Figure 16); however, confidence in the trend is limited because of the small number of data points. The change in sensitivity stayed within  $\pm 20\%$  of initial calibration.

Individual dosimeter results for the change in sensitivity with the time elapsed from the end of the exposure until dosimeter reading (Figures 17–21) confirm the average trends for sensitivity change for both test dates (Figures 22–24): In general, the number of observed bubbles (i.e., sensitivity) increases with time after the end of exposure. The increase is approximately 2%–4% in the first 24 hours, then climbs to 4%–6% in the next 24 hours (48 hours after the end of exposure), reaches 10% in the next 24 hours (72 hours after the end of exposure), and ranges between 10% and 20% in the next 72 hours (144 hours after the end of exposure). This small increase in the number of the bubbles after the end of exposure may be explained by assuming that some bubbles are too small to be counted immediately after the end of the exposure but then may gradually increase in size as evaporation continues due to the fact that the pressure of the gel is insufficient to fully immobilize them. Thus the bubbles eventually reach sufficient size to be counted some time after exposure. This effect is relatively small and may be considered to be within the uncertainties associated with neutron dose determination. The change in sensitivity over longer periods of times after the end of exposure was not investigated because the manufacturer recommends keeping the dosimeters under pressure when not in use (i.e.,



reading the exposed dosimeters as soon as feasible and repressurizing them as soon as possible).

## **CONCLUSION**

Our tests indicate that BD-PND dosimeters of very high sensitivity may have a useful life of at least 6 months, with a response (i.e., sensitivity) within  $\pm 25\%$  of the calibration values established by the manufacturer, if the recommendations for use and storage are followed. For bubble dosimeters of very high sensitivity, no definite trend was established for the change in sensitivity with the time after initial calibration, although a small increase in the number of bubbles with the time after end of exposure was observed. Some individual bubble dosimeters may exhibit wider fluctuations of sensitivity with time.

Based on the available test information on BD-PND dosimeters from this and other publications and from the manufacturer's information, the following recommendations for extending the useful life of bubble dosimeters can be derived:

- When not in use, BD-PNDs should be kept in their airtight aluminum storage containers.
- Storage temperature should be kept between 10°C and 30°C.
- Temperature during use should be kept between 20°C and 37°C.
- BD-PNDs should be read and repressurized within 3 days of the end of exposure or before the number of accumulated bubbles (which is proportional to the received dose) exceeds 350.

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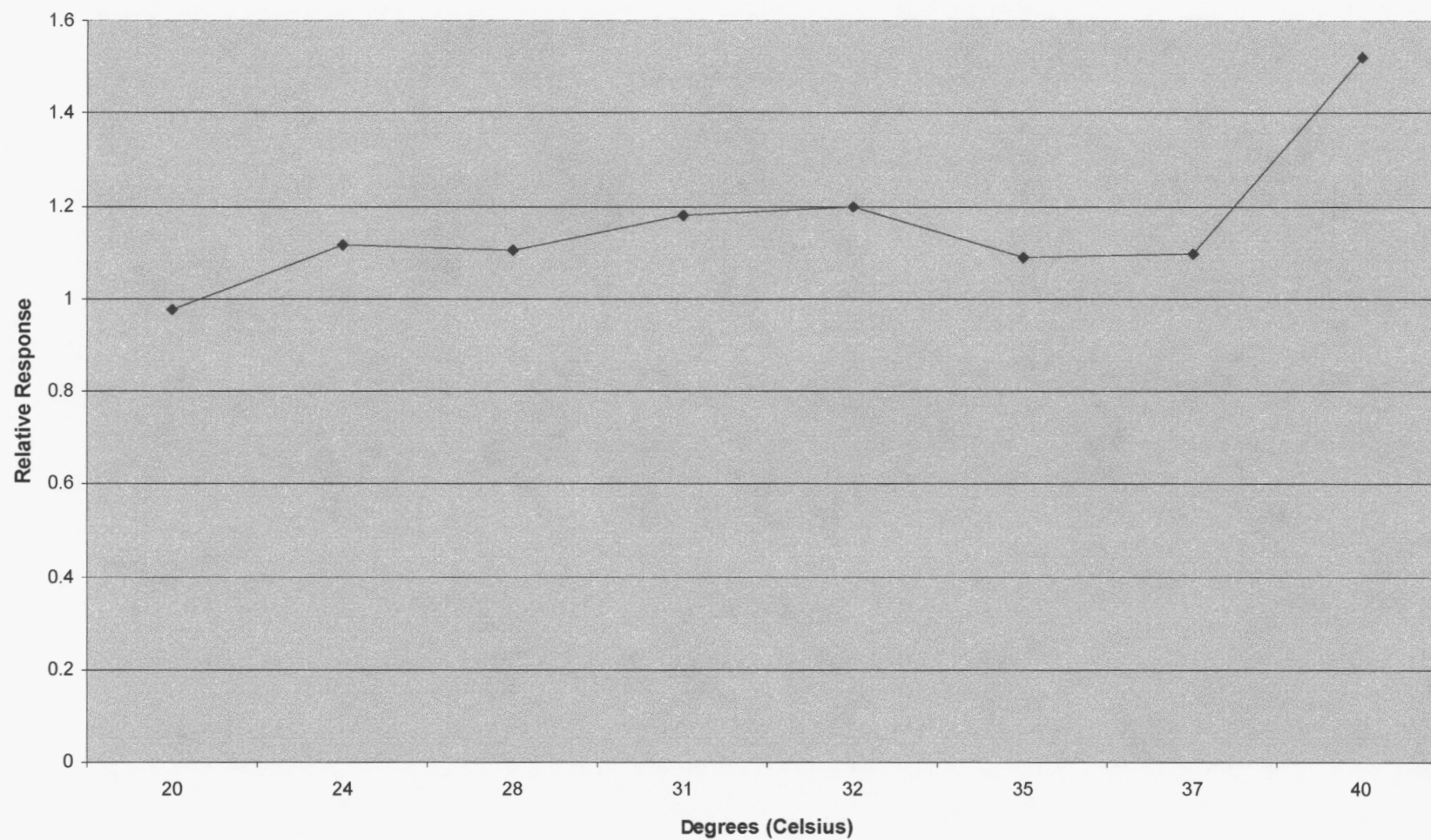
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## TABLES AND FIGURES

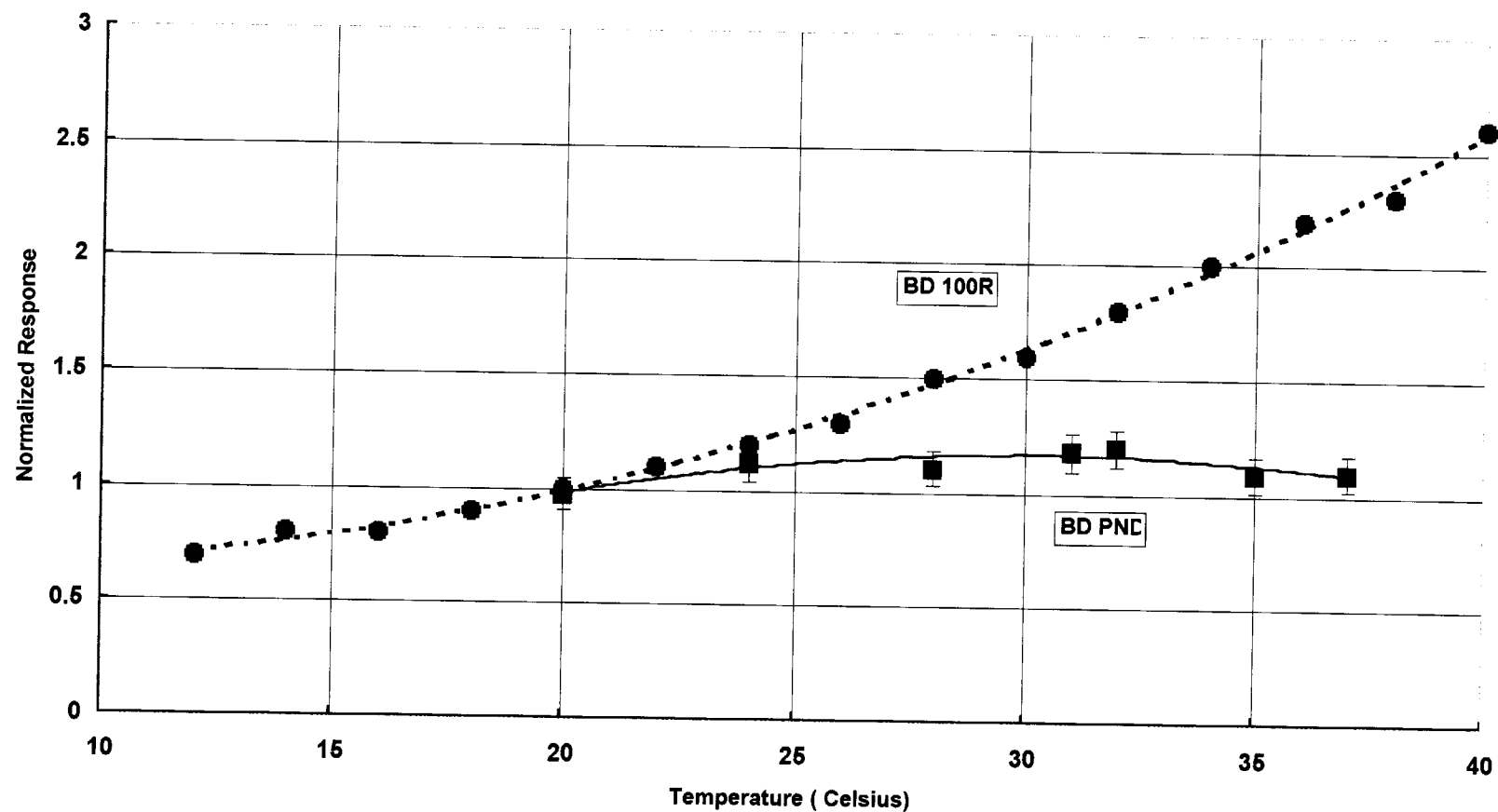
**Table 1 Exposure characteristics for the tested bubble dosimeters**

Group designation	Calibration date	Dosimeter #	Sensitivity (bubbles/mrem)	Distance (cm)	Exposure time (min)	Delivered dose (mrem)
B#1 total of 80 dosimeters	3/31/1999	109504	2.1	100	10 - 15	14 - 20
		111375	2.2			
		113231	2.3			
		110527	2.3			
		113783	2.3			
		114087	2.3			
		119612	2.3			
		112764	2.4			
		117439	2.5			
		120699	2.6			
		107027	2.7			
		112637	3.2			
BH#1 total of 32 dosimeters	10/13/1999	118356	20	200 - 300	10 - 15	2 - 5
		118210	19			
BH#2 total of 32 dosimeters	1/14/2000	120115	16	200 - 300	10 - 15	2 - 5
		123878	16			
BH#3 total of 35 dosimeters	4/20/2000	118307	24	200 - 300	10 - 15	2 - 5
		114406	25			
		123841	28			
		122137	31			
		123885	20			
BH#4 total of 35 dosimeters	8/10/2000	128086	17	200	10 - 15	3.3-5.0
		127998	18			
		132887	19			
		118308	20			
		129032	20			

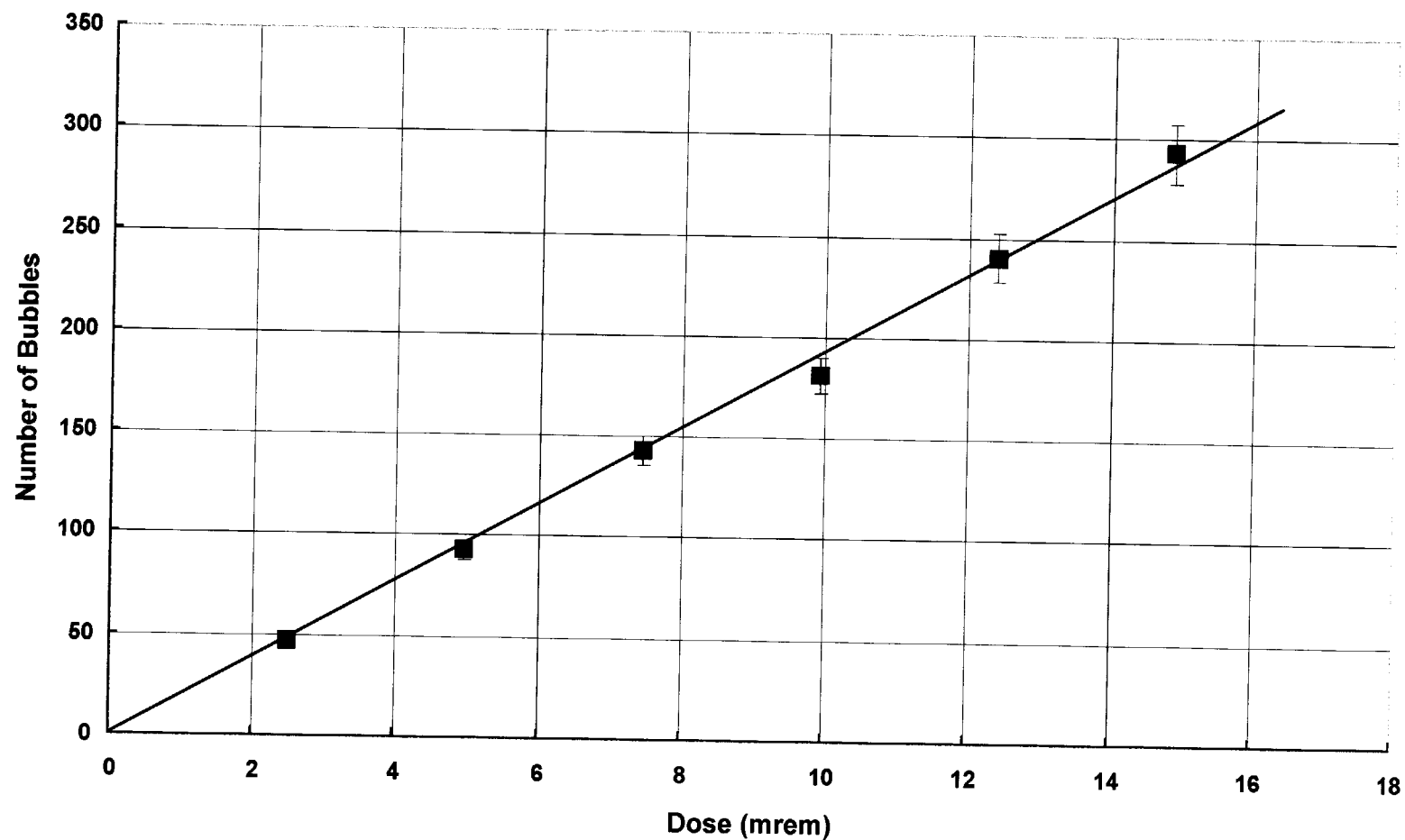
**Figure 1**    **Temperature response of BD-PND dosimeters (provided by BTI).**



**Figure 2**    **Temperature response of BD 100R and BD PND dosimeters (provided by BTI).**



**Figure 3** Dynamic range for BD PND dosimeter—with recompression between measurements (provided by BTI).



**Figure 4**    **Dynamic range for BD PND dosimeters—without recompression between measurements (provided by BTI).**

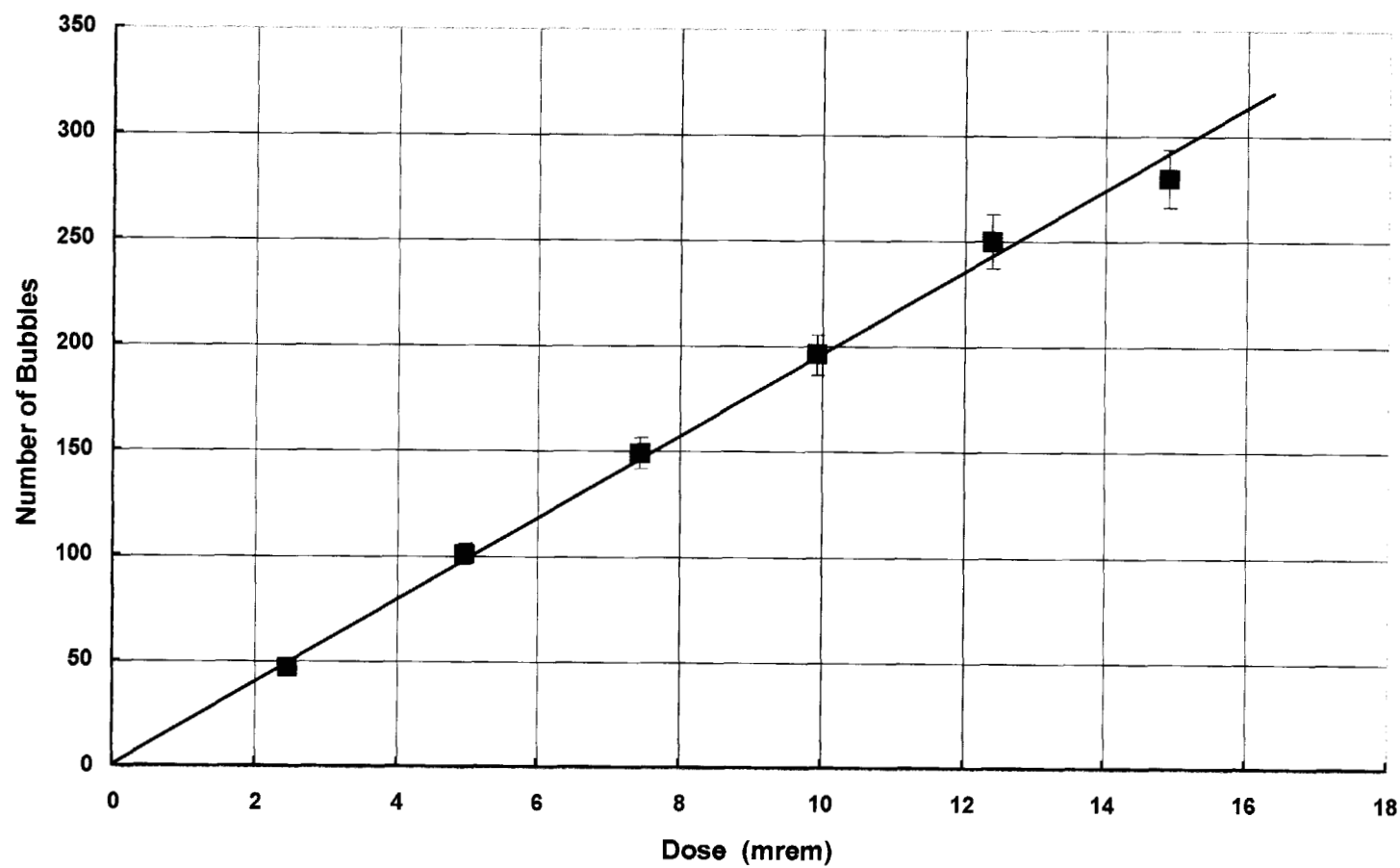
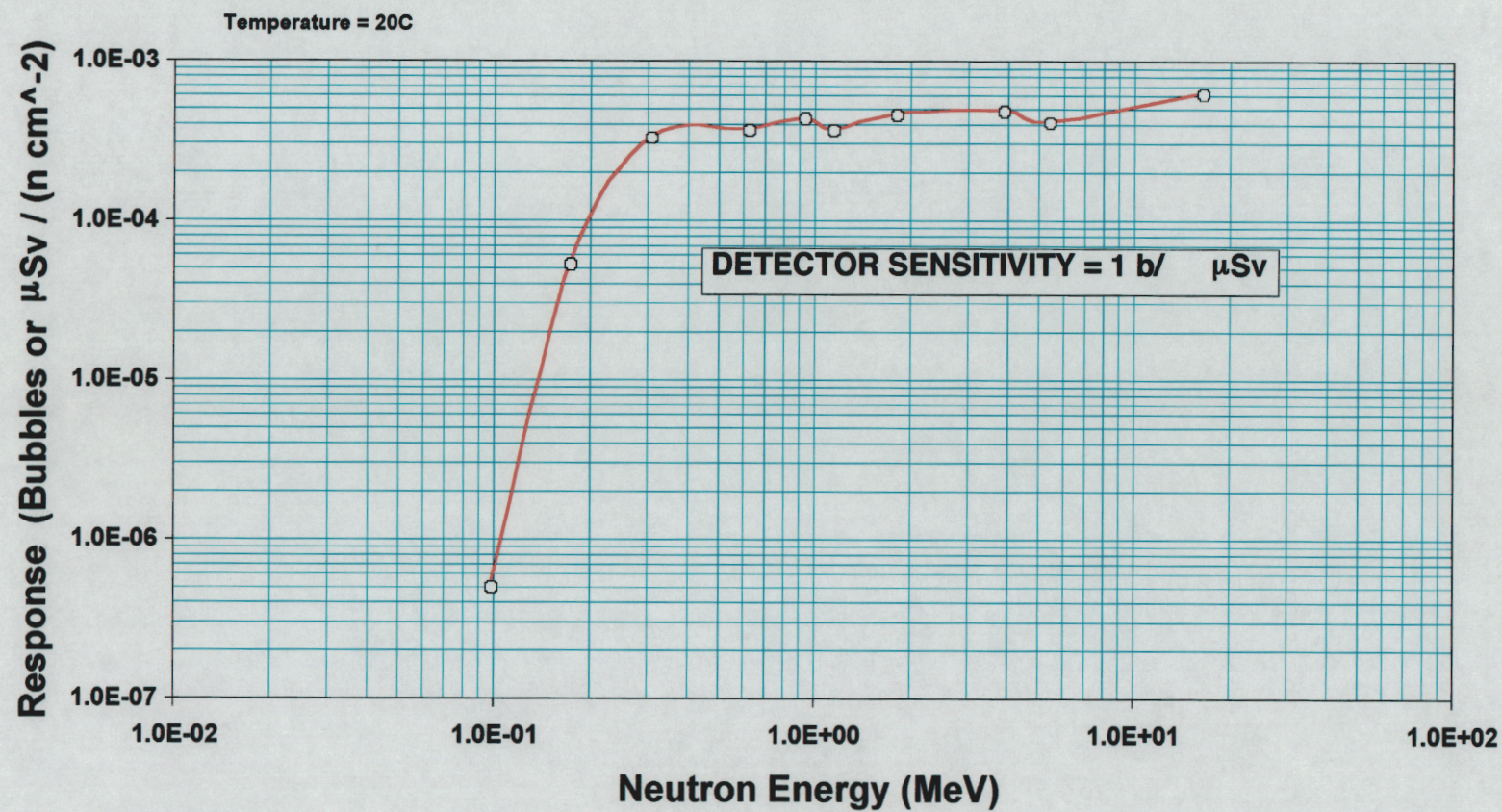




Figure 5 Energy response of BD PND dosimeters (provided by BTI).



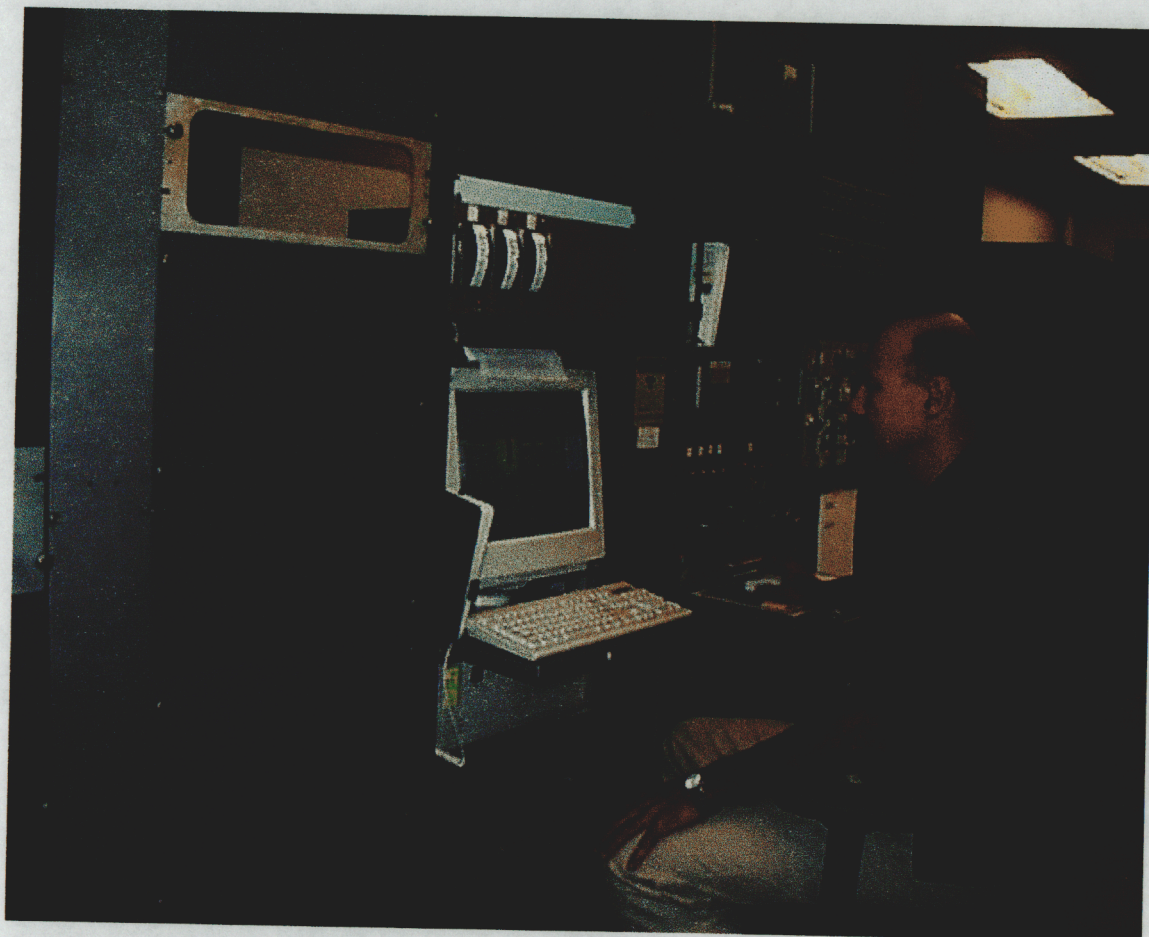


**Figure 6** BDR-III bubble dosimeter reader connected to a personal computer.



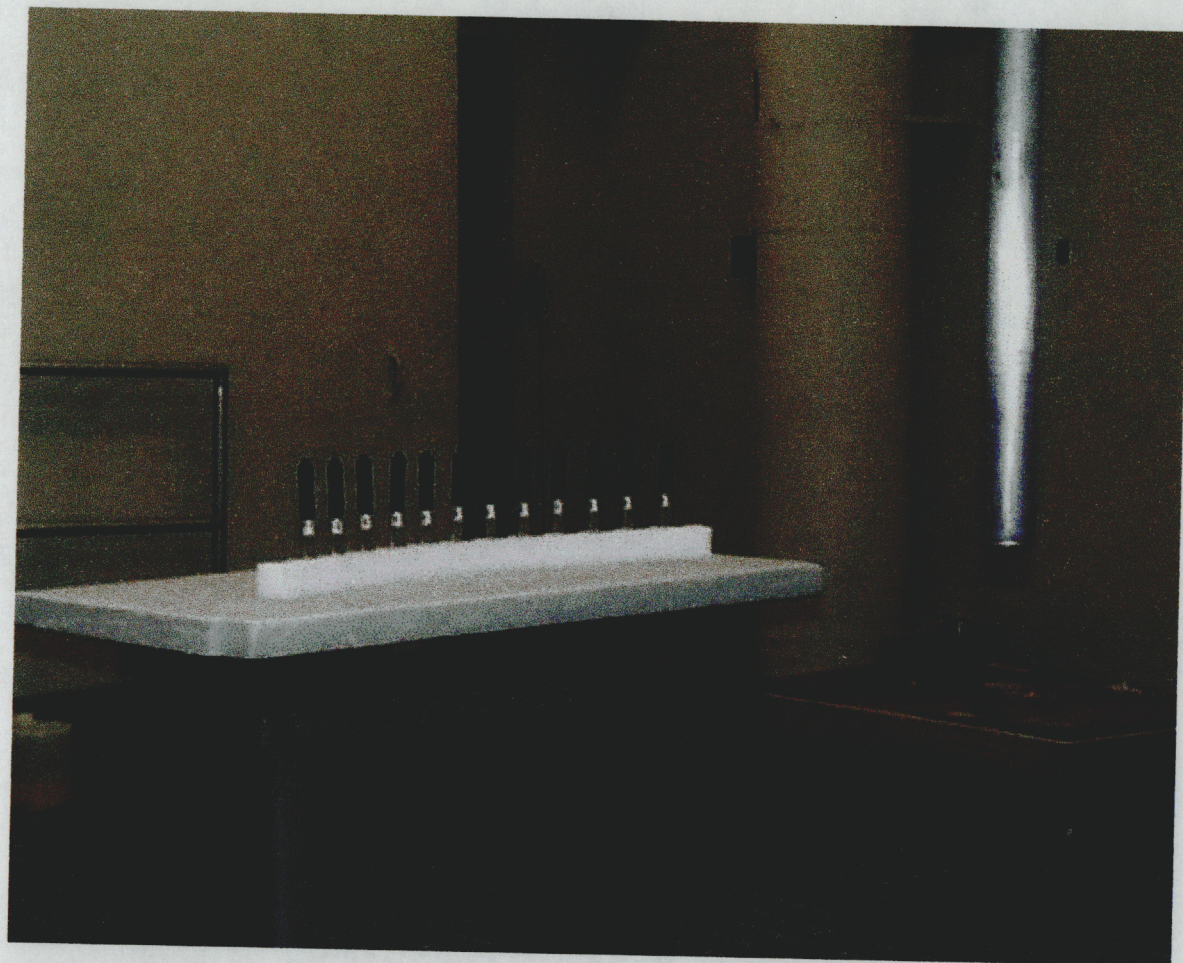


**Figure 7** Control panel of the pneumatic transport system.



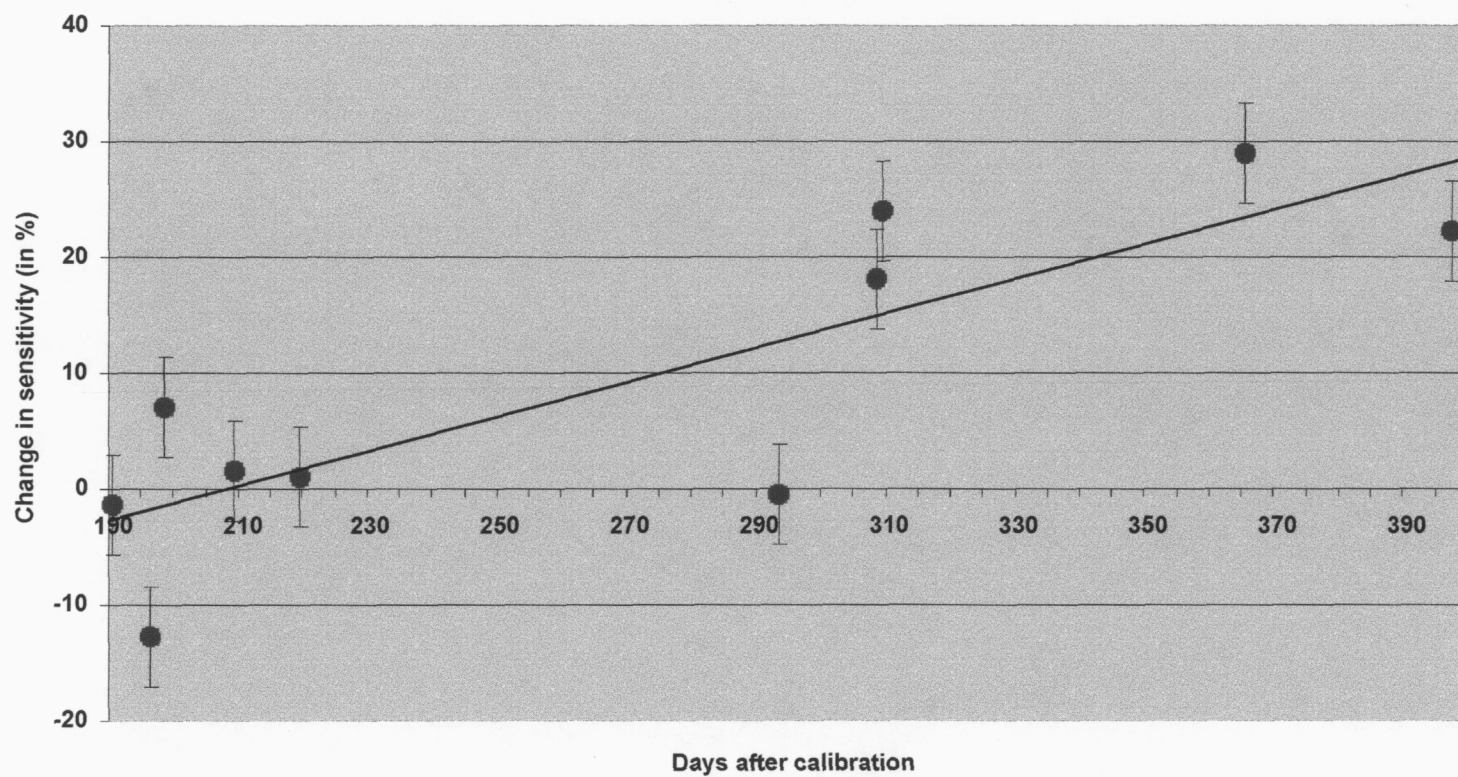


**Figure 8** Experimental setup with 12 BD-PNDs. The Cf source is pneumatically transported to the end of the aluminum tube.

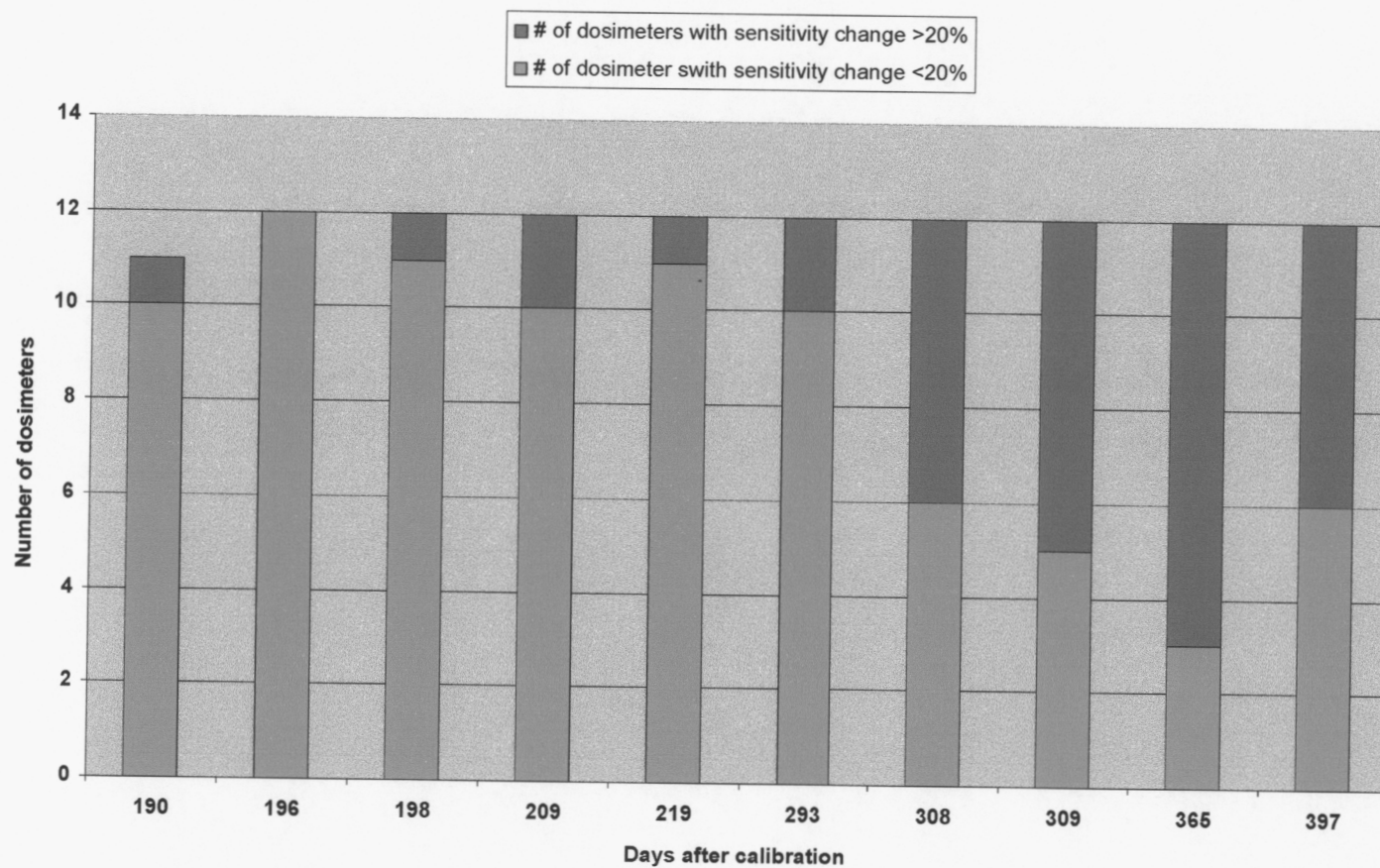




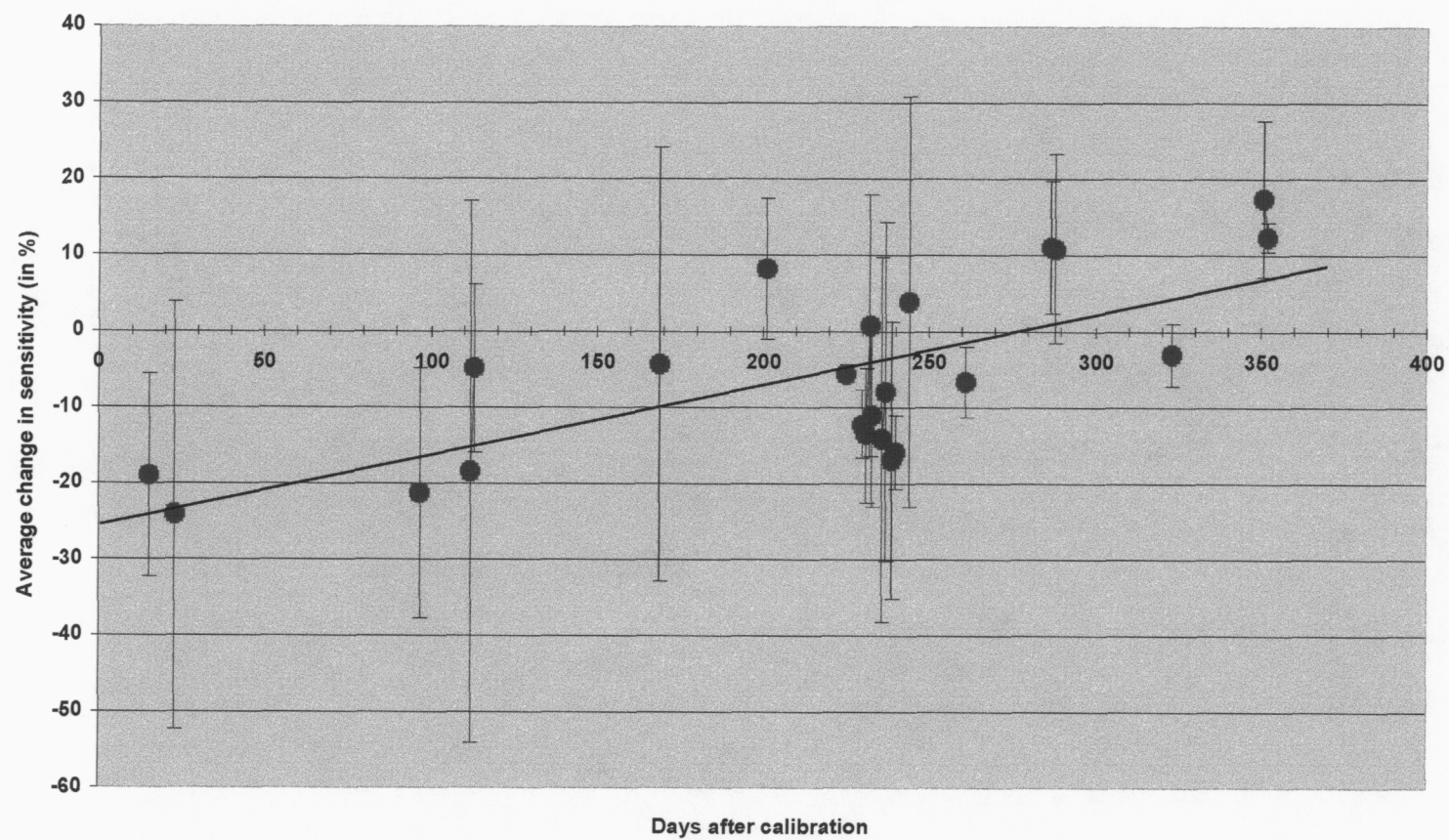
**Figure 9** Average change in sensitivity for 12 dosimeters (medium sensitivity, group B#1, calibration date 3/31/99).



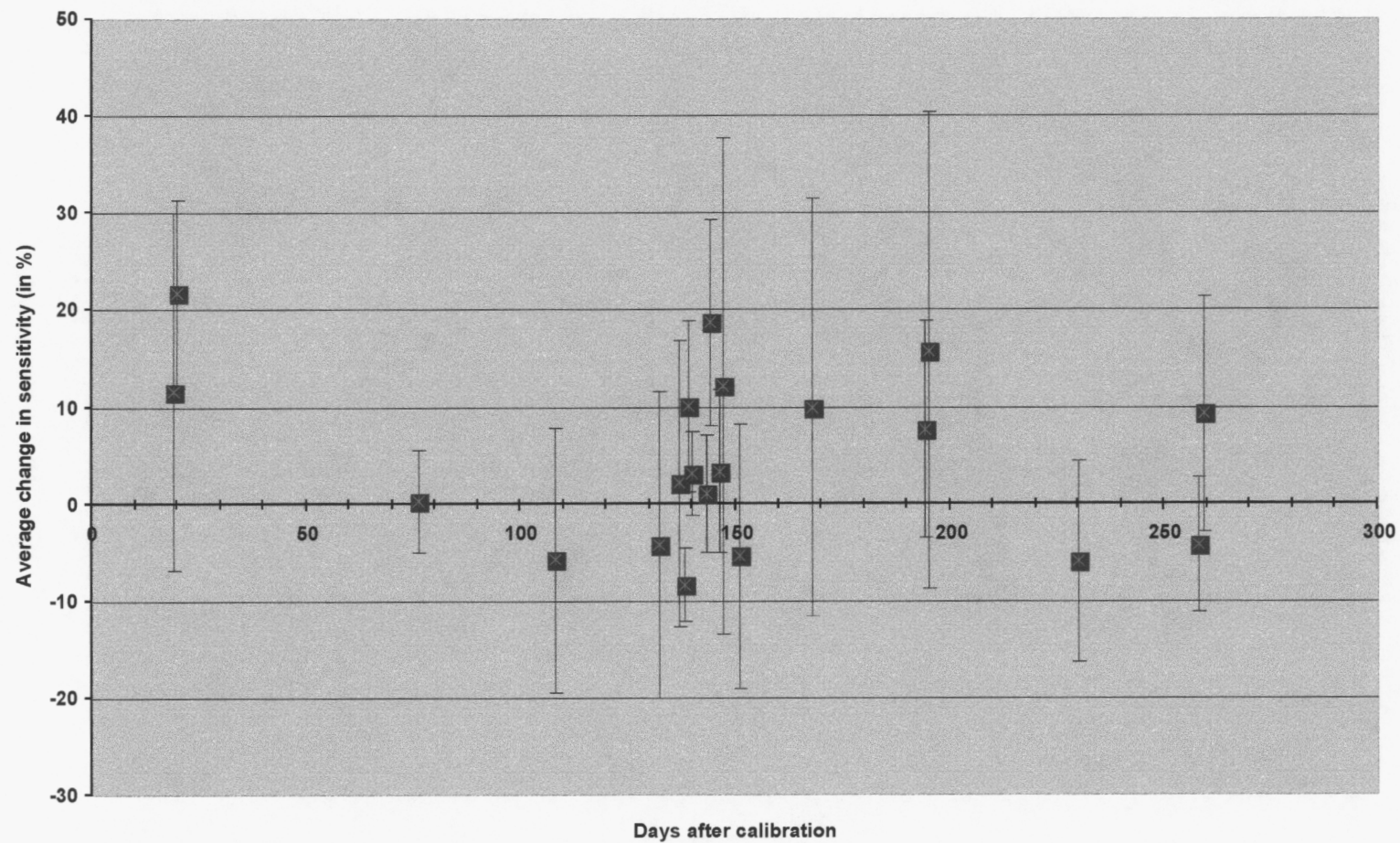
**Figure 10** Number of dosimeters with change of sensitivity >20% from group B#1 (12 dosimeters).



**Figure 11** Average change in sensitivity for two dosimeters (group BH#1, calibration date 10/13/99).

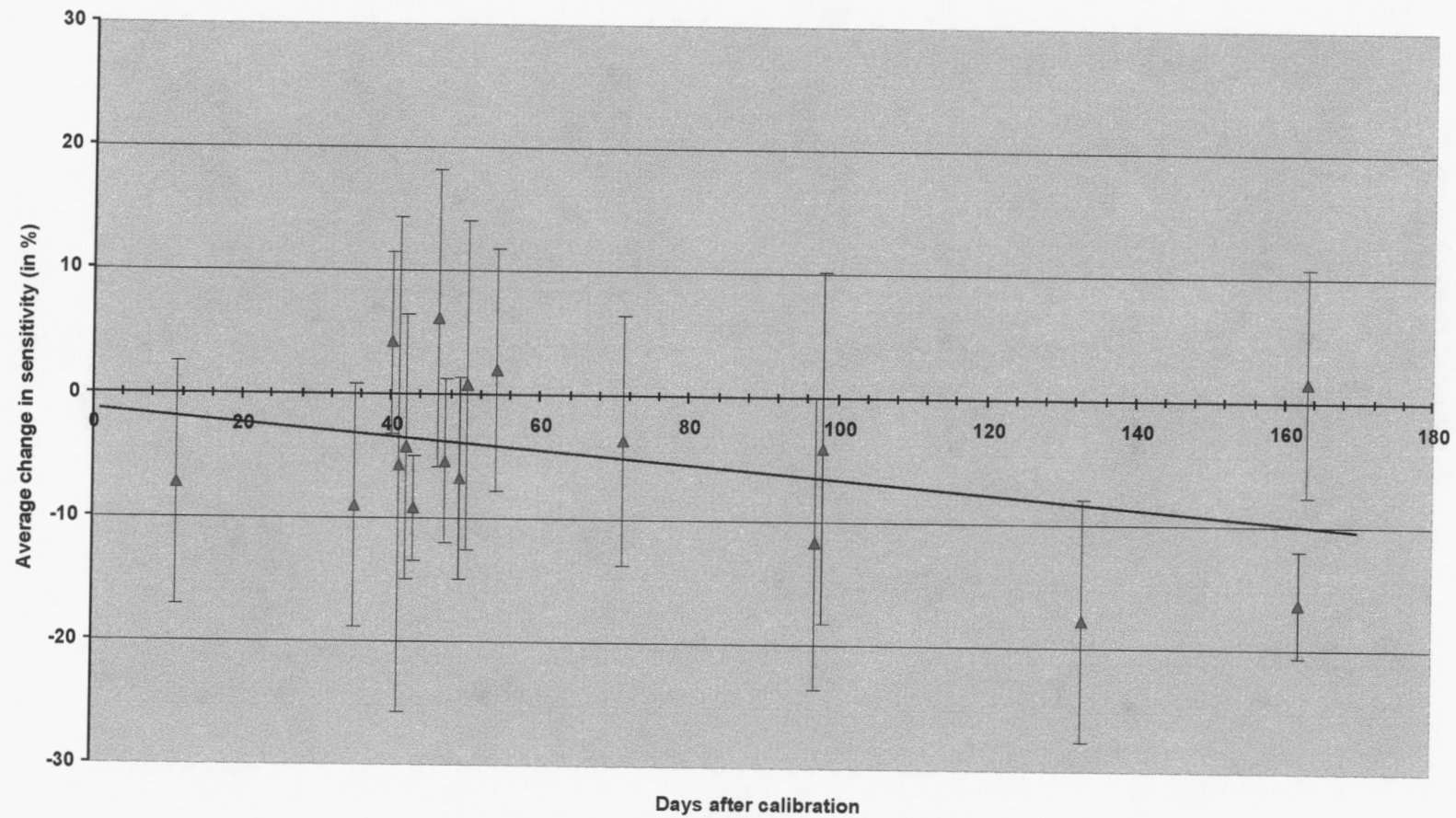


**Figure 12** Average change in sensitivity for two dosimeters (group BH#2, calibration date 1/14/00).

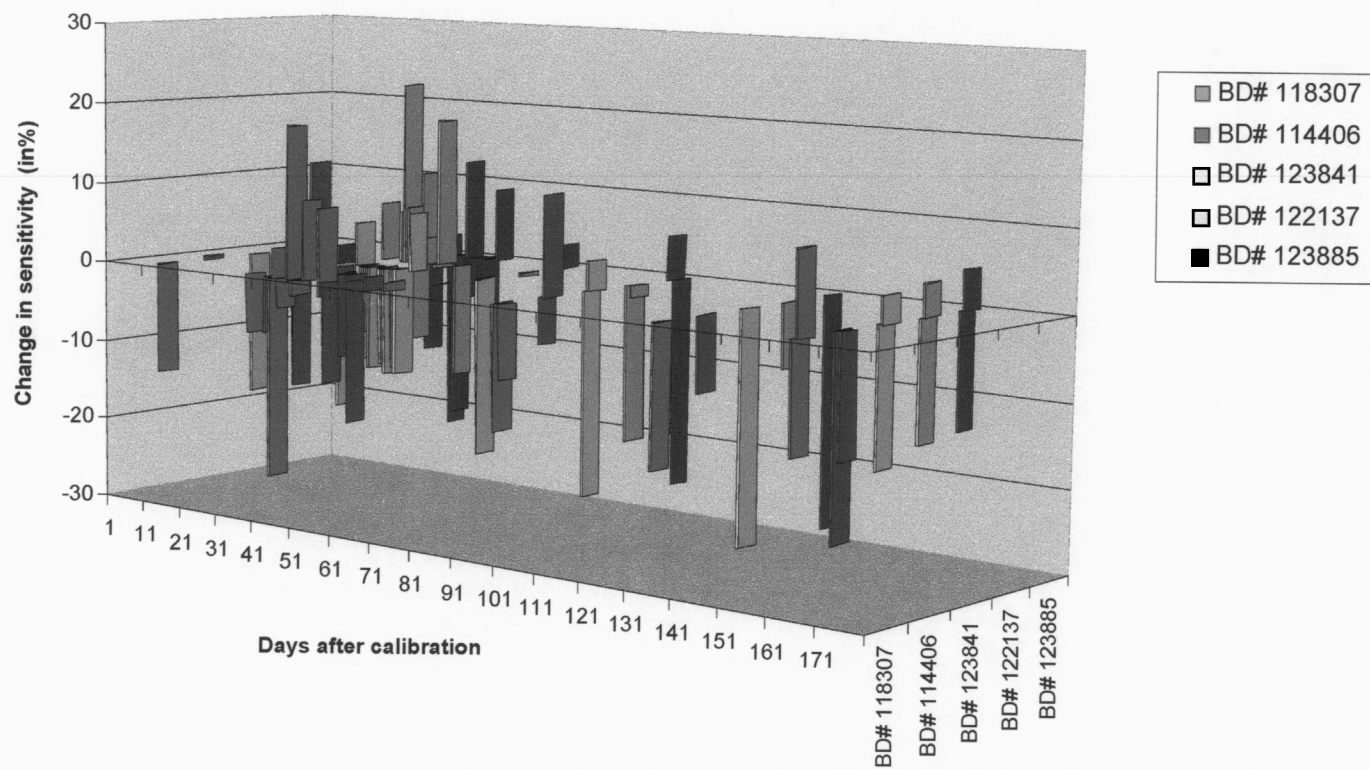




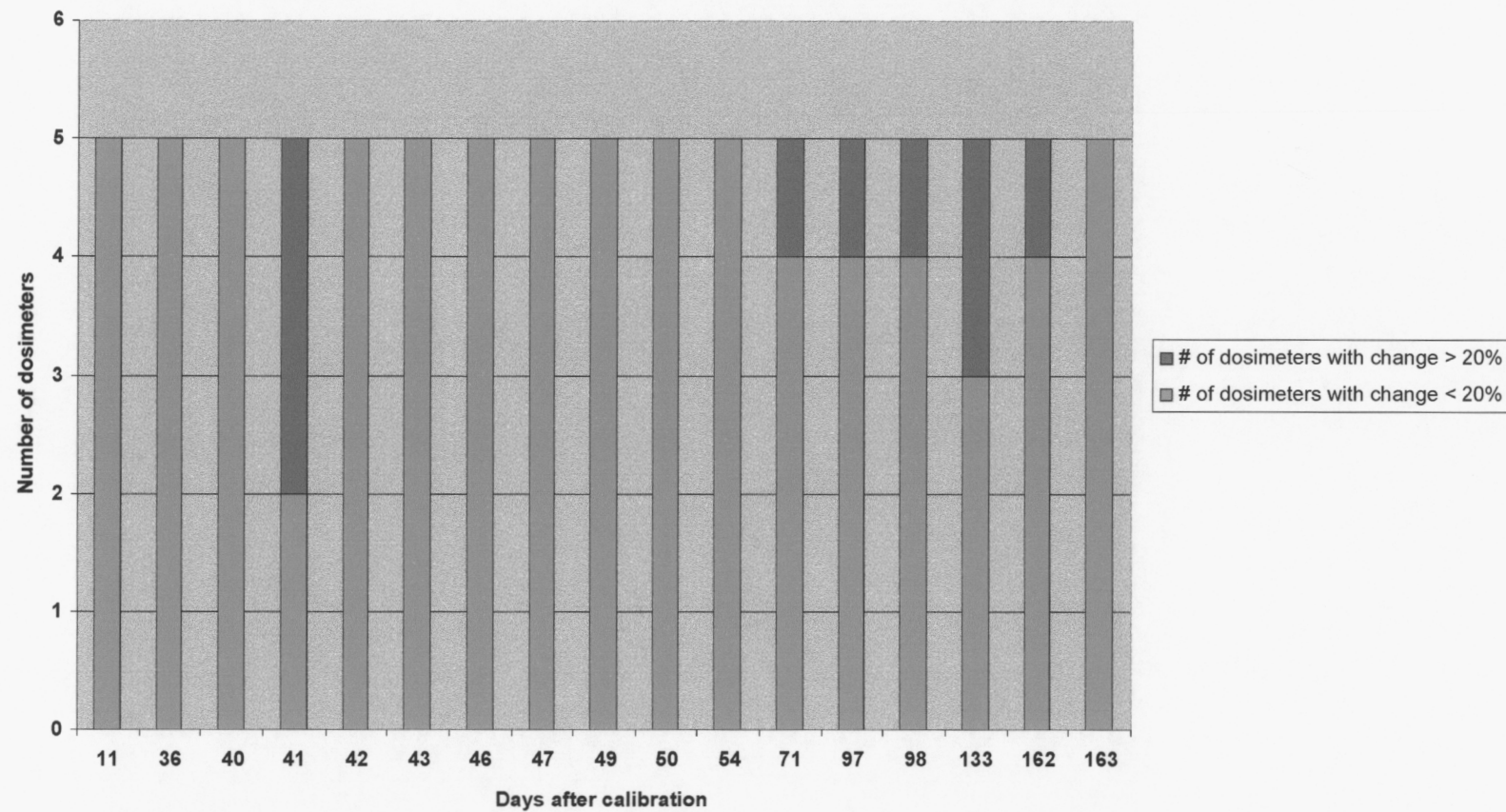
**Figure 13** Average change in sensitivity for five dosimeters (group BH#3, calibration date 4/20/00).



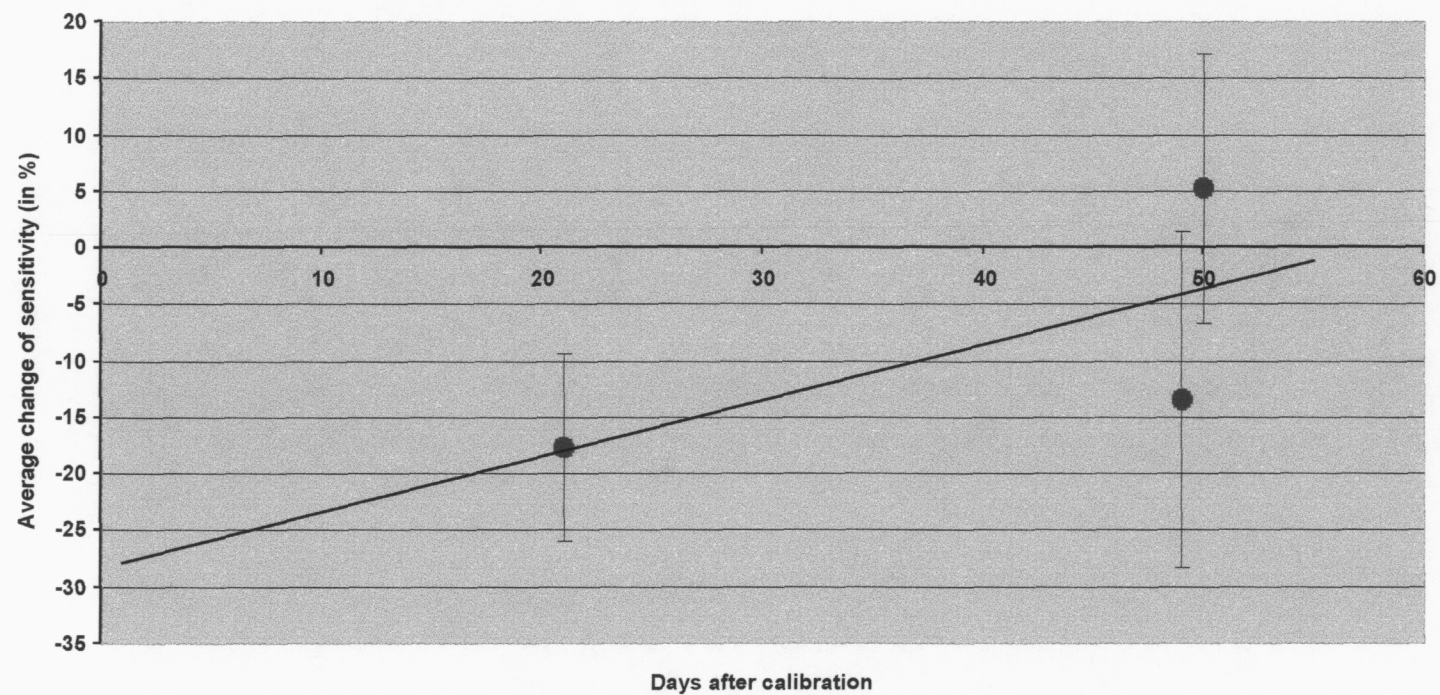
**Figure 14 Individual change in sensitivity for each dosimeter from group BH#3 (calibration date 4/20/00).**



**Figure 15** Number of dosimeters with sensitivity change >20% from group BH#3 (five dosimeters).

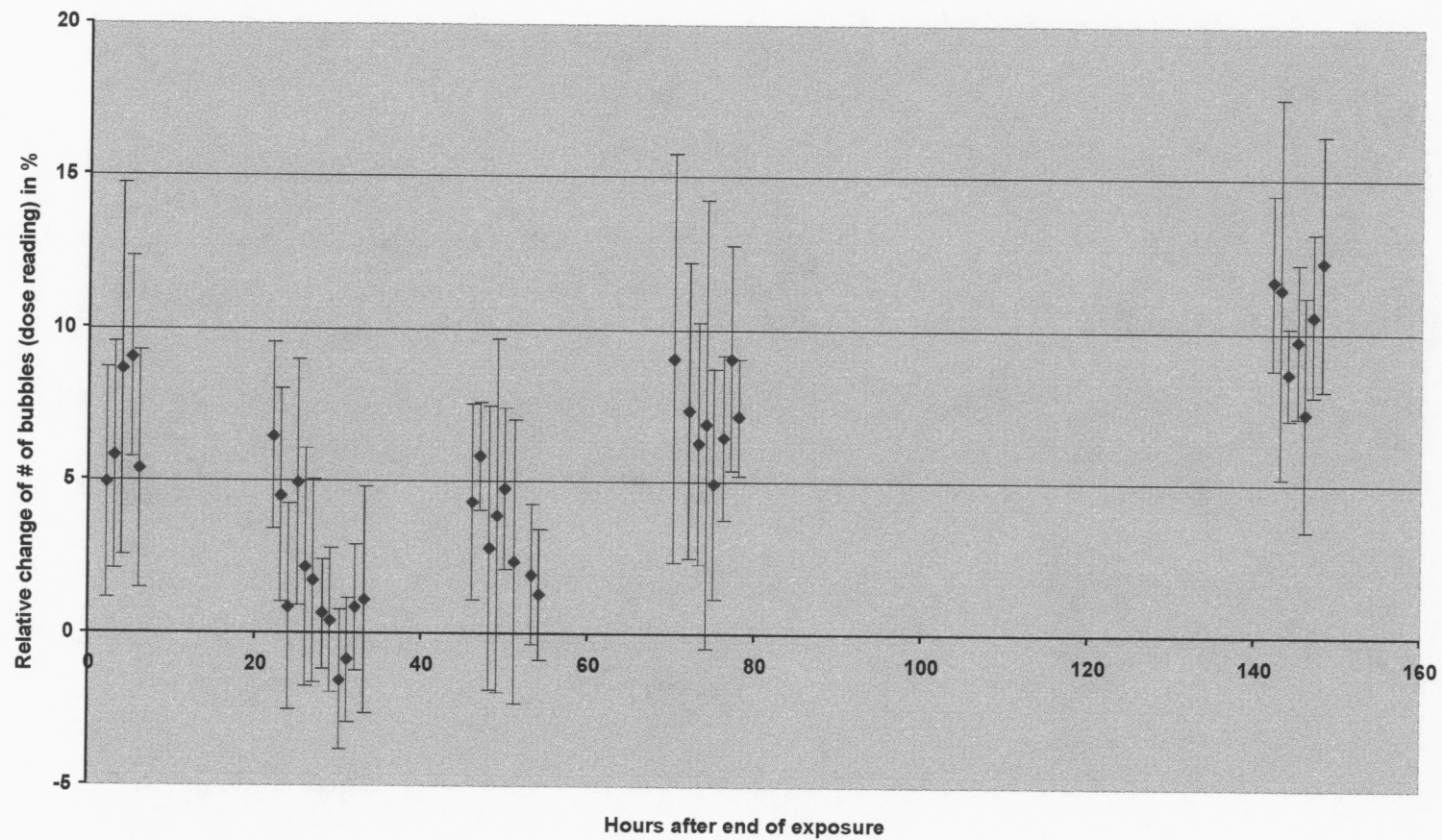


**Figure 16** Average change of sensitivity for five dosimeters (group BH#4, calibration date 8/10/00).

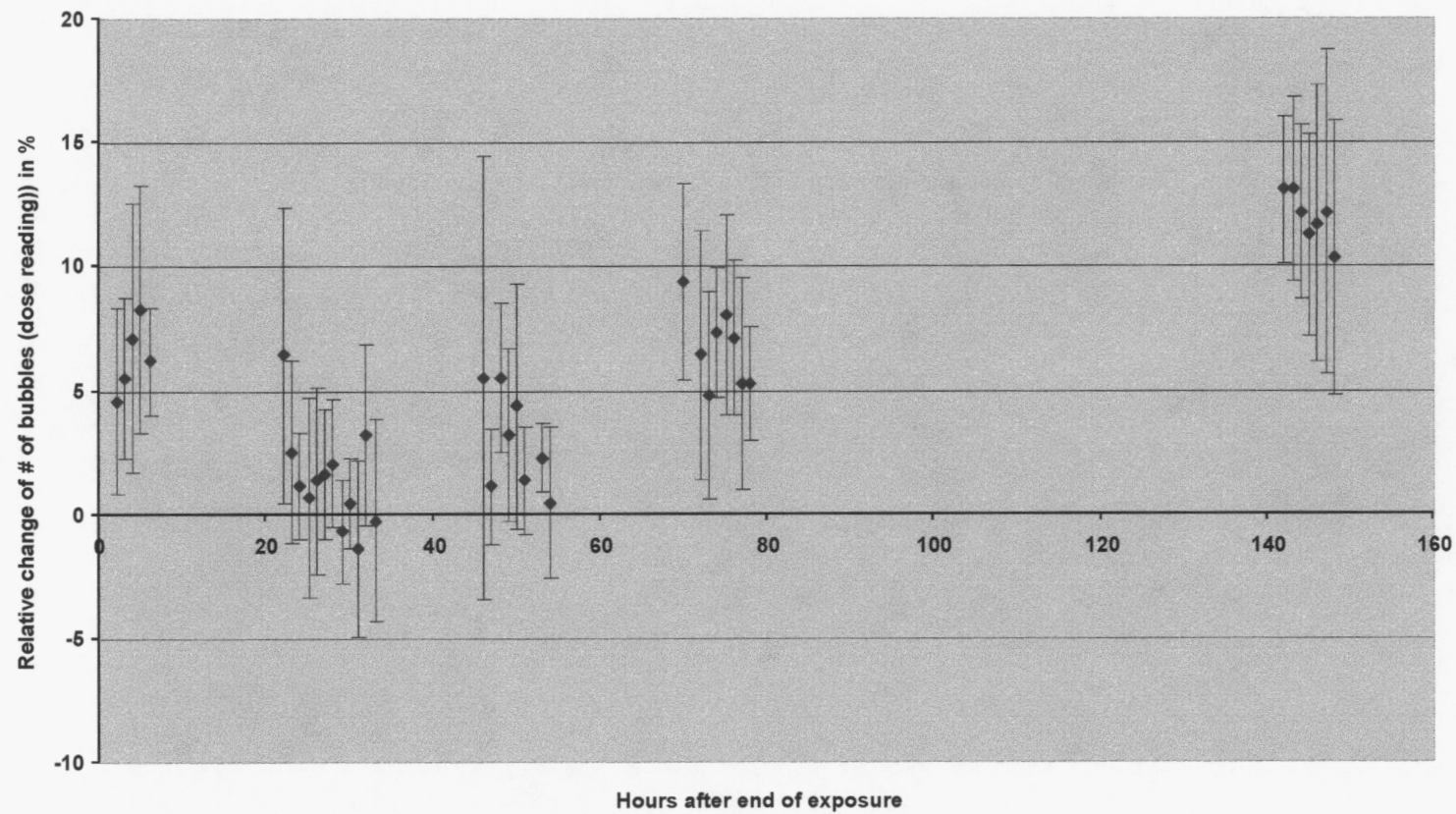




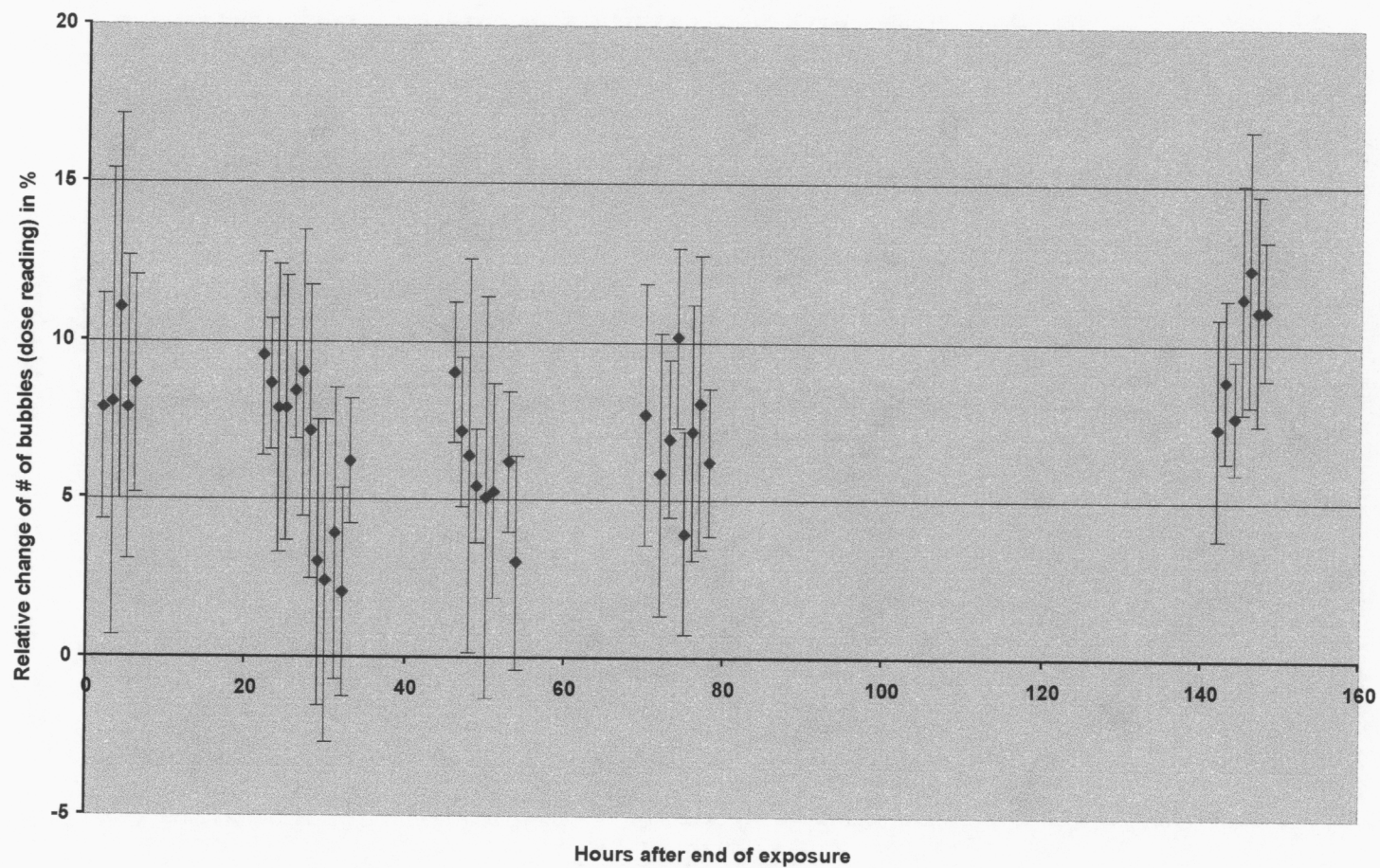
**Figure 17** Change in the number of the bubbles after end of exposure on 6/13/00 (dosimeter #118307 of group BH#3).



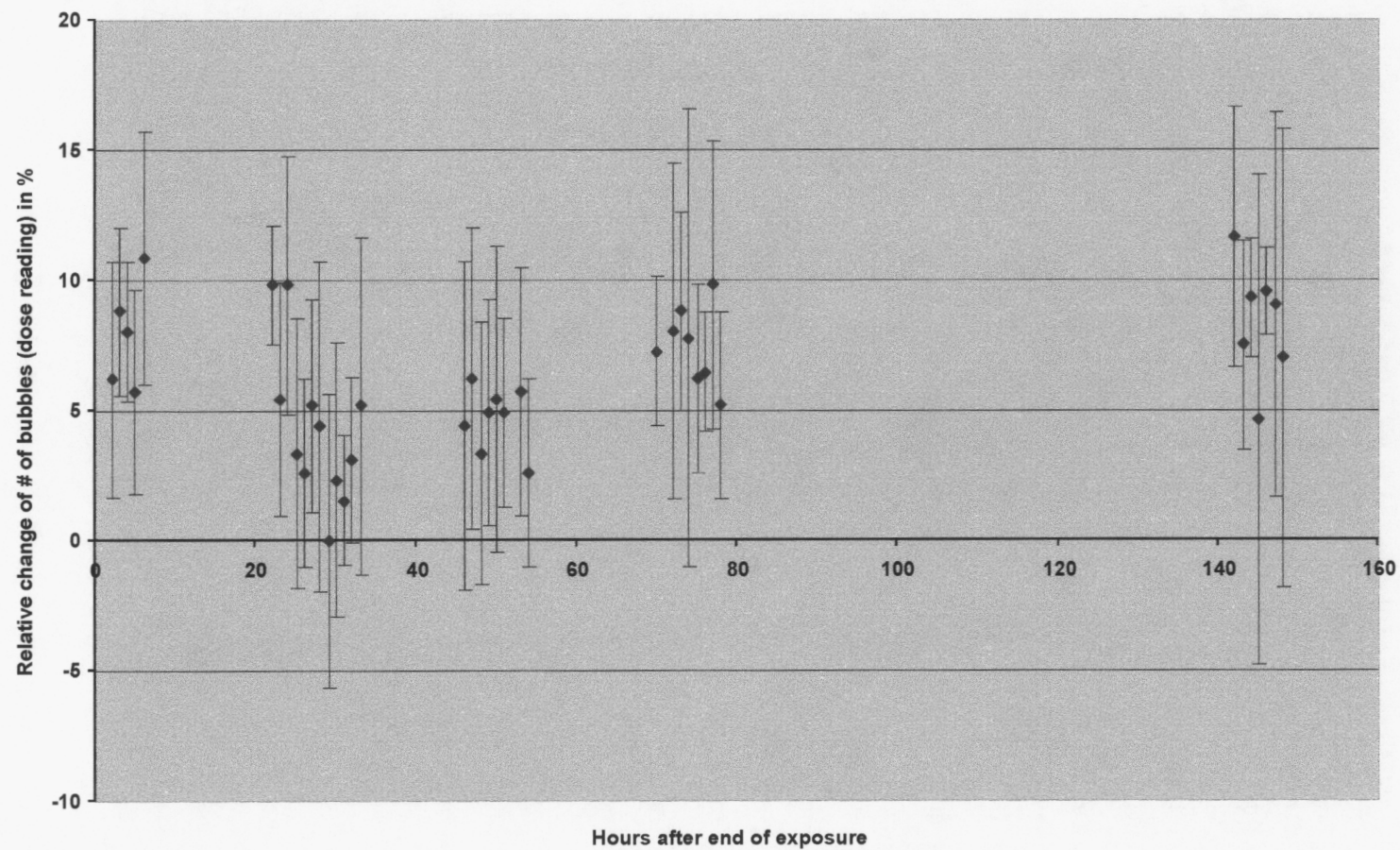
**Figure 18**      **Change in the number of the bubbles after end of exposure on 6/13/00 (dosimeter #114406 of group BH#3).**



**Figure 19**      **Change in the number of the bubbles after end of exposure on 6/13/00 (dosimeter #124841 of group BH#3).**

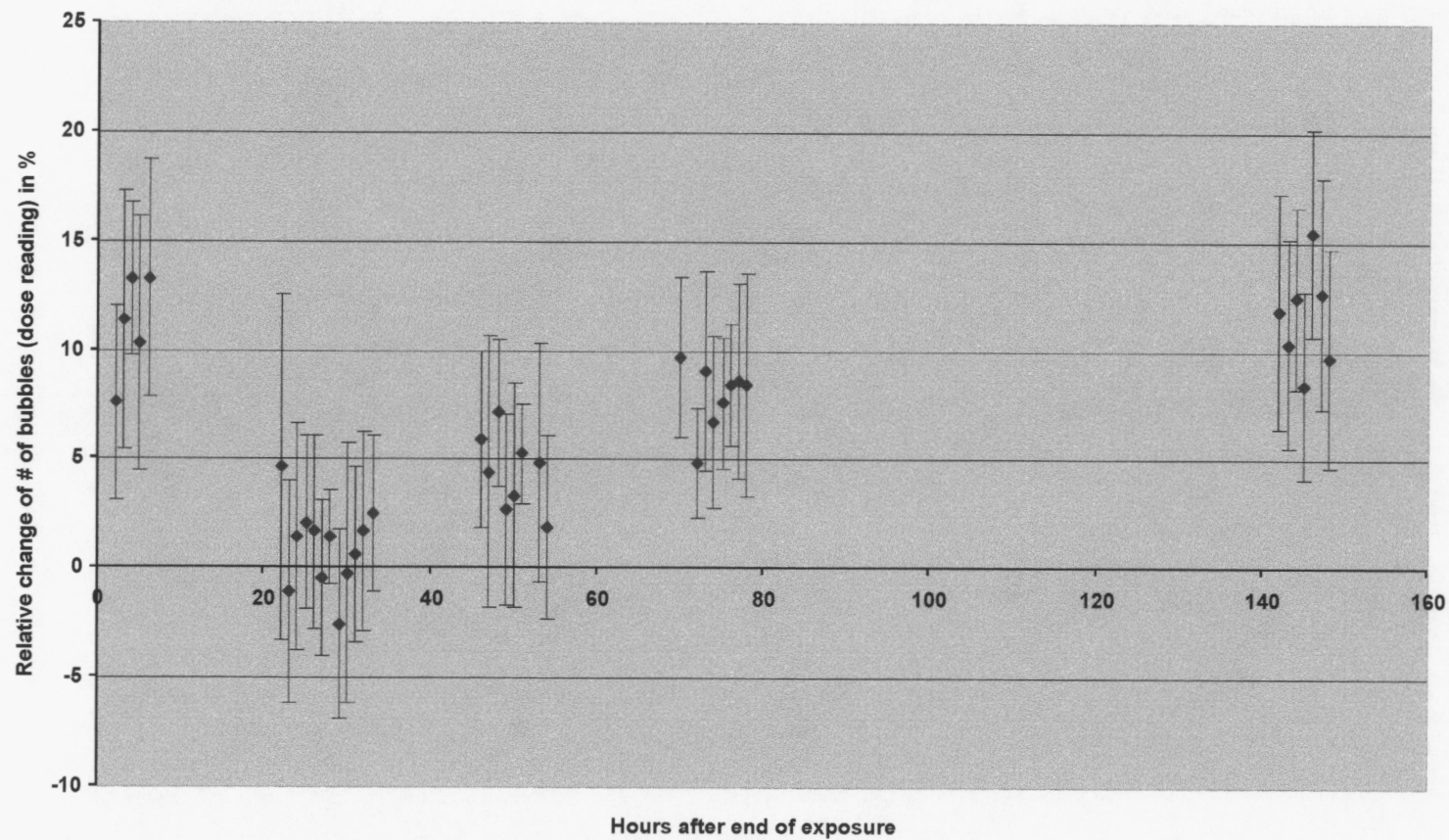


**Figure 20** Change in the number of the bubbles after end of exposure on 6/13/00 (dosimeter #123885 of group BH#3)

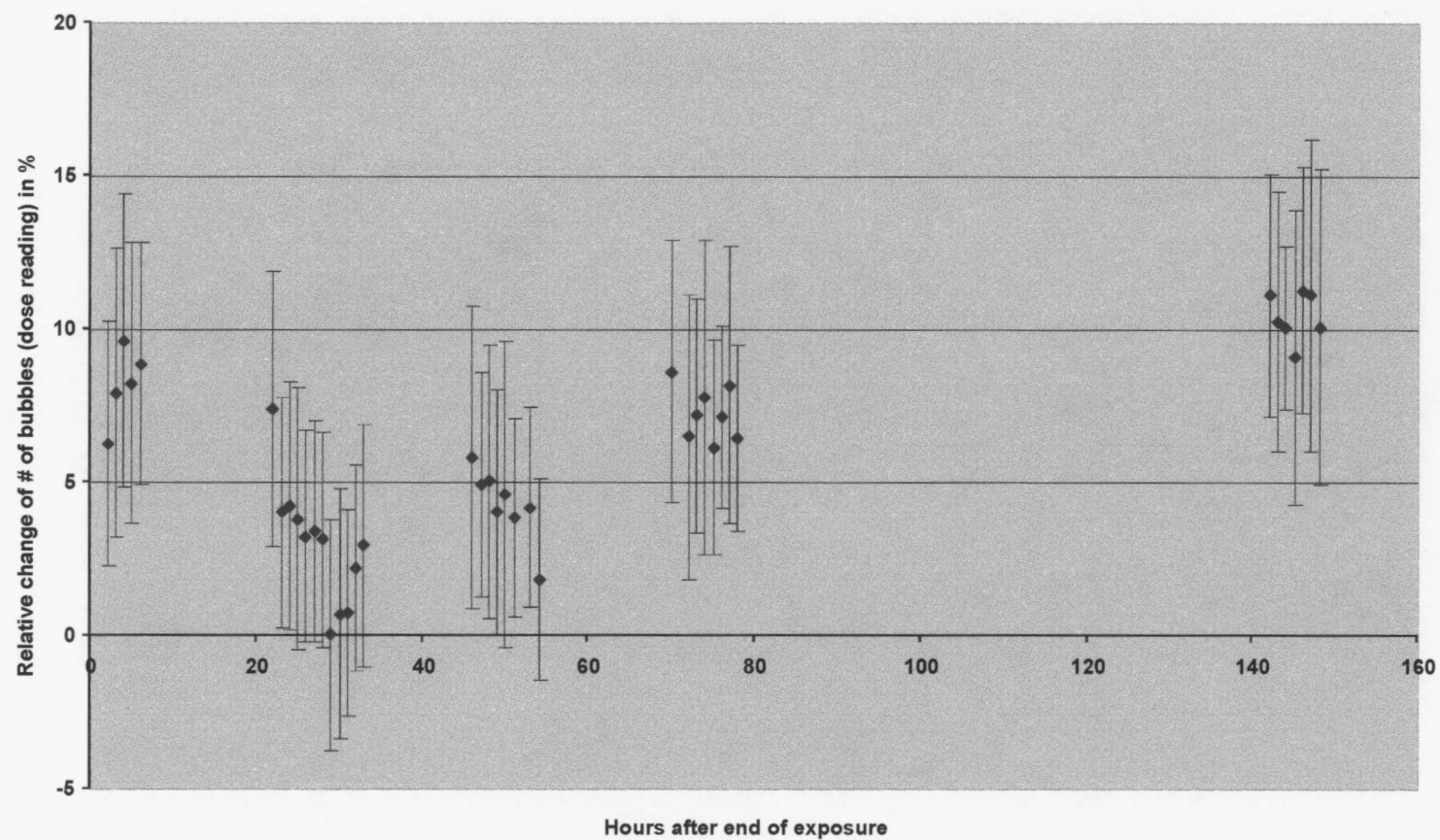




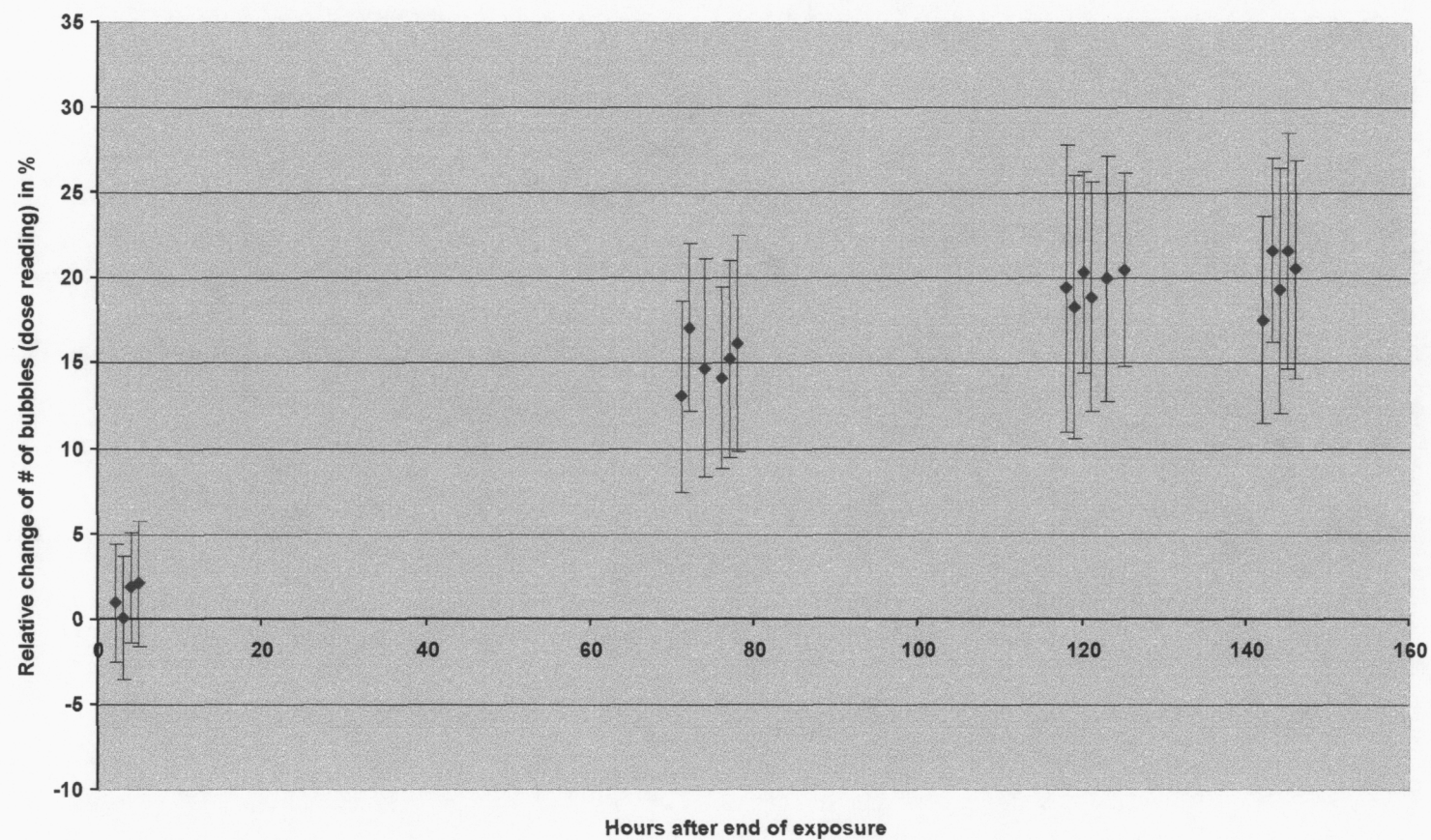
**Figure 21** Change in the number of the bubbles after end of exposure on 6/13/00 (dosimeter #122137 of group BH#3)



**Figure 22** Averaged change in the number of bubbles after end of exposure on 6/13/00 (all five dosimeters from group BH#3).



**Figure 23** Averaged change in the number of bubbles after end of exposure on 6/30/00 (all five dosimeters from group BH#3).



**Figure 24** Averaged change in the number of bubbles after end of exposure on 6/13/00 and 6/30/00 (all five dosimeters from group BH#3).

